REAL-TIME ERROR CONTROL FOR SURGICAL SIMULATION

Huu Phuoc Bui,[1,2] Satyendra Tomar,[2] Hadrien Courtecuisse,[1] Stéphane Cotin,[3] and Stéphane Bordas.[2]
[1]University of Strasbourg, CNRS, ICube, F-67000 Strasbourg, Fance, [2]University of Luxembourg, Research Unit of Engineering Science, L-1359 Luxembourg, Luxembourg, and [3]Inria Nancy-Grand Est, F-54600 Villers-lès-Nancy, France.

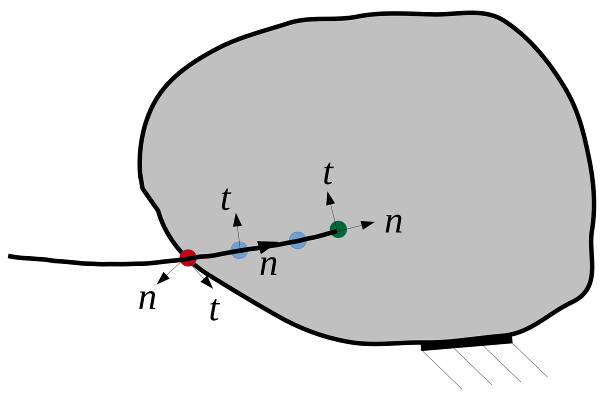
OBJECTIVE

To present the first real-time a posteriori error-driven adaptive finite element approach for real-time simulation, and to demonstrate the method on a needle insertion problem.

METHODS

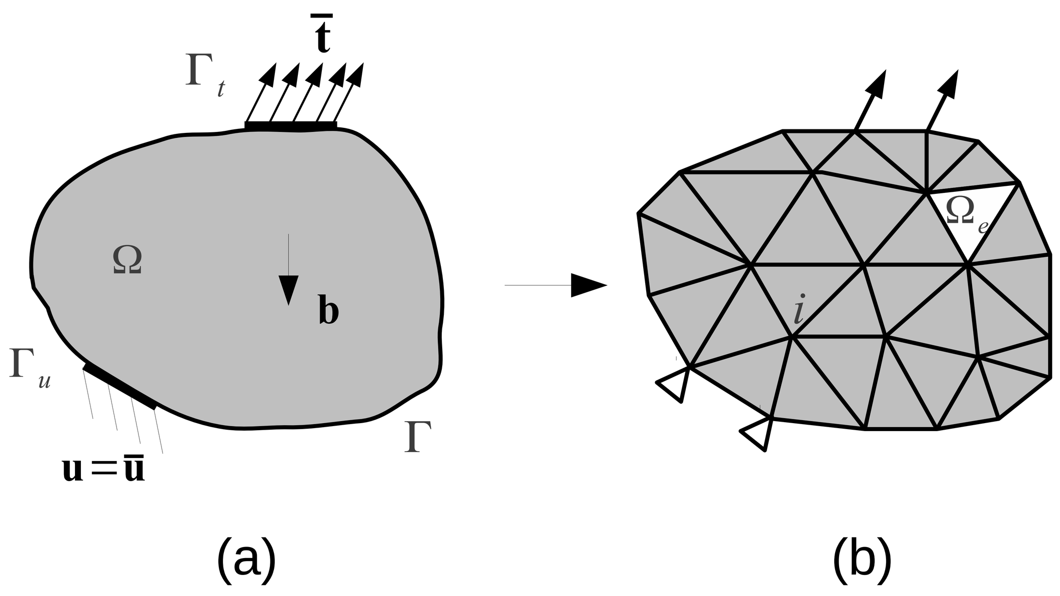
We use corotational elasticity and a frictional needle/tissue interaction model based on friction. The problem is solved using finite elements within SOFA. The refinement strategy relies upon a hexahedron-based finite element method, combined with a posteriori error estimation driven local h-refinement, for simulating soft tissue deformation.

FIGURE 1



Three types of constraints between the needle and soft tissue: surface puncture (in red), needle tip constraint (in green) and needle shaft constraints (in blue). A local coordinate system *n-t* is defined at each constraint point.

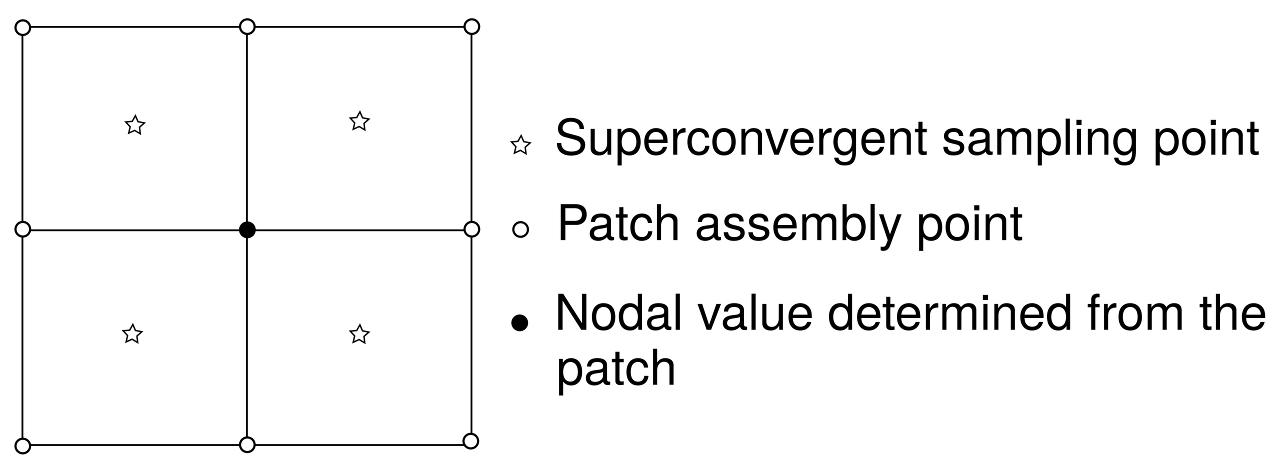
FIGURE 2



A body Ω subjected to a traction $\bar{\mathbf{t}}$ on Γ_t, a body force $\mathbf{b}$, and an imposed displacement $\bar{\mathbf{u}}$ on Γ_u (a); Simplified illustration of FEM discretization (b).

Zienkiewicz-Zhu smoothing procedure (Zienkiewicz and Zhu, 1992):

FIGURE 3



The smoothed gradient is obtained from an element patch.

We define the approximate error of an element Ω_e as

$$\eta_e = \sqrt{\int_{\Omega^e} (\epsilon^h - \epsilon^s)^T (\sigma^h - \sigma^s) \mathrm{d}\Omega}, \tag{1}$$

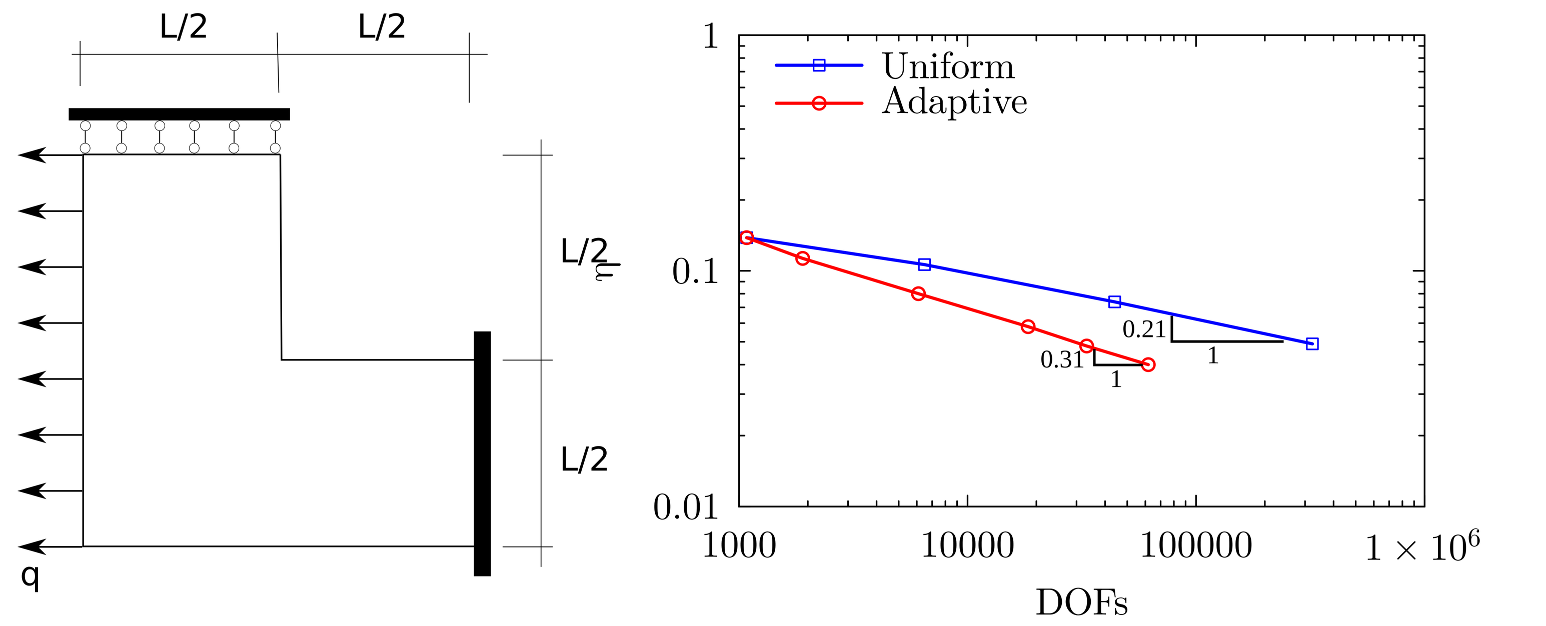
which is the energy norm of the distance between the FEM solution (denoted by h) and an improved solution (denoted by s). We mark an element for refinement if

$$\eta_e \geq \theta \eta_M \text{ with } 0 < \theta < 1 \text{ and } \eta_M = \max_e \eta_e. \tag{2}$$

RESULTS

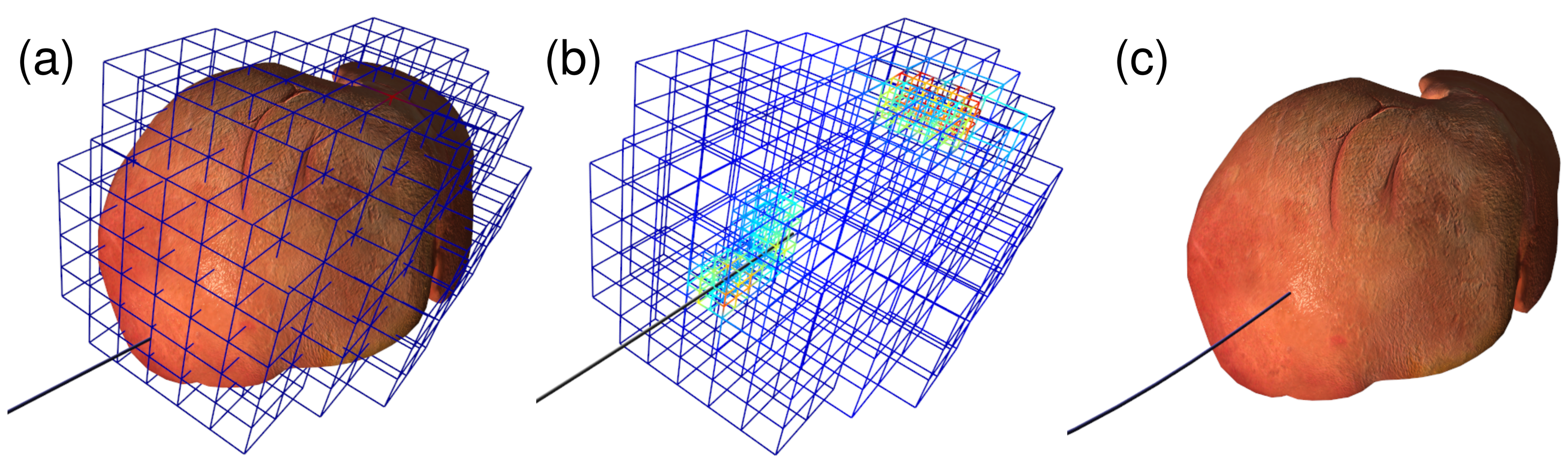
We control the local and global error level in the mechanical fields (e.g. displacement or stresses) during the simulation. We show the convergence of the algorithm on academic examples, and demonstrate its practical usability on a percutaneous procedure involving needle insertion in a liver. For the latter case, we compare the force displacement curves obtained from the proposed adaptive algorithm with that obtained from a uniform refinement approach (see Bui et al., 2016).

FIGURE 4



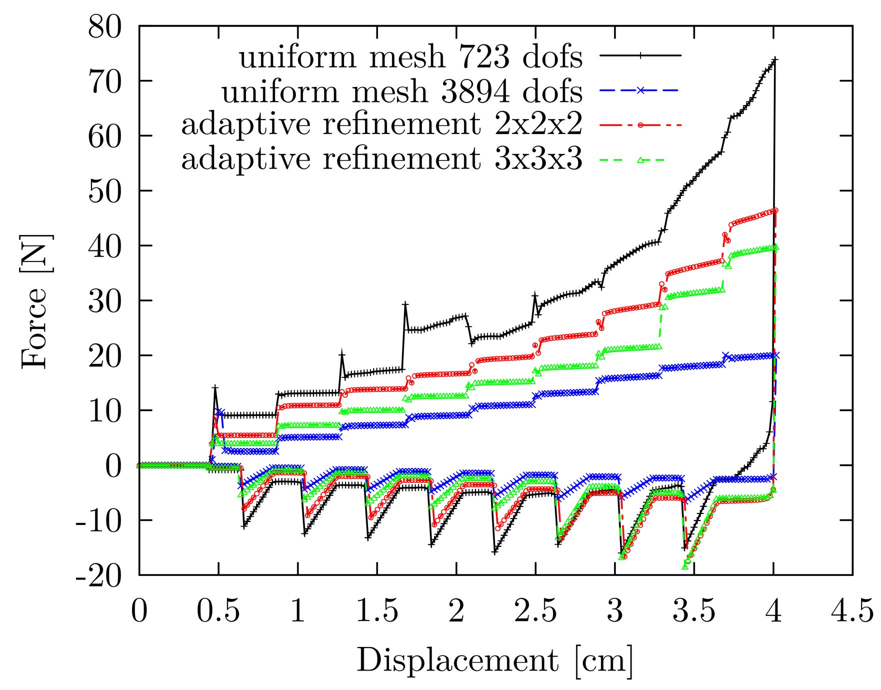
Convergence of the relative error on L-shaped domain test, comparison between uniform and adaptive refinements.

FIGURE 5



(a) Simulation of needle insertion in a liver; (b) using dynamic mesh refinement scheme driven by error estimate; (c) visual depiction.

FIGURE 6



Needle-liver phantom interaction force during needle insertion and pullback. The interaction force varies due to advancing friction and tissue cutting strength, globally increases (with positive values) during the insertion stage. At 4 cm of the needle-tip displacement, the needle is retracted and the interaction force changes the direction, varies due to retrograding friction, globally decreases and gets zero when the needle is completely pulled out. The max DOFs when using the adaptive refinement schemes $2 \times 2 \times 2$ and $3 \times 3 \times 3$ is 1071 and 2193, respectively.

CONCLUSIONS

- Error control guarantees that a tolerable error level is not exceeded during the simulations
- Local mesh refinement accelerates simulations
- Our work provides a first step to discriminate between discretization error and modeling error by providing a robust quantification of discretization error during simulations.

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- University of Strasbourg, USIAS (BPC 14/Arc 10138)
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